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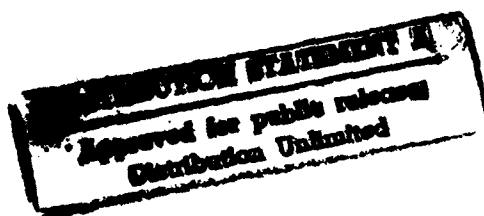
Application of Photogrammetry
of F-14D Store Separation.

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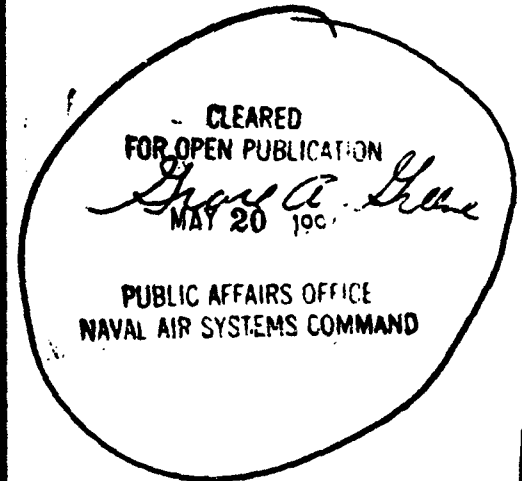
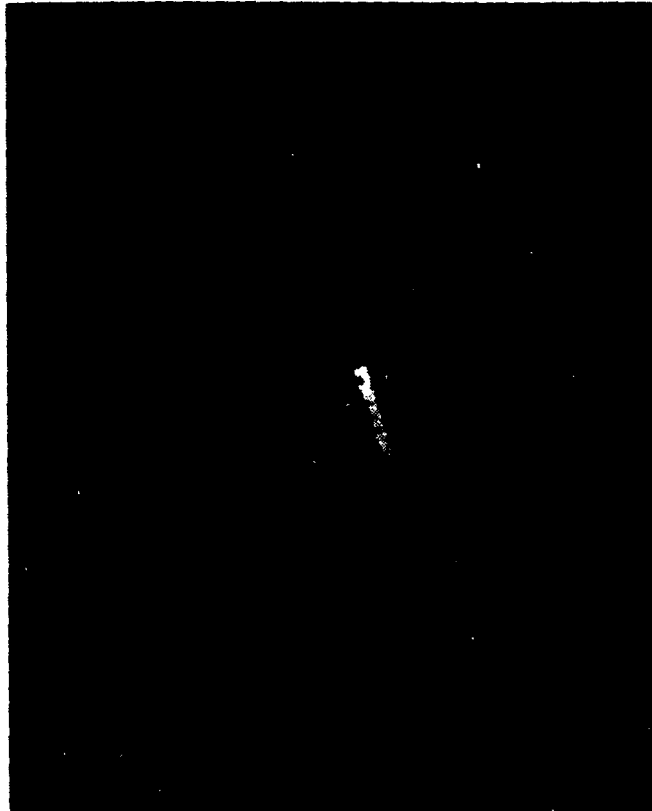
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INTRODUCTION

Conceived in the 1960's as a replacement for the F-4 Phantom, the 'A' variant of the F-14 Tomcat was first deployed as an air superiority fighter in the early 1970's. Designed as a follow-on to the F-14A, the F-14D was introduced to the U.S. Navy in 1990. Improvements were manifold and included addition of the A/N-AAS-429 Infrared Search and Track Set (IRSTS) to the 'chin' pod located beneath the radome forward of the nose landing gear. This chin pod, which was smaller and housed only the A/N AXX-1 Television Camera Set (TCS) in the F-14A variant, was postulated to adversely affect air-to-air and air-to-ground weapon separation from the aircraft fuselage stations. This warranted additional testing to validate the separation envelope previously tested and authorized on the F-14A.

In an attempt to bring state-of-the-art separation prediction techniques to the F-14D weapon certification program, the Navy's flight clearance authority mandated the use of wind tunnel generated predictions to minimize program risk. Validation of the air-to-ground predictions, performed at the Naval Air Warfare Center - Aircraft Division, NAS Patuxent River, MD required a precise method by which store six-degree-of-freedom motion could be determined. Several methods of obtaining this quantitative data were evaluated with photogrammetric analysis selected as the most suitable. While tailored for the particular application detailed in this paper, photogrammetry may be used wherever precise position and orientation of objects in three-dimensional space is a requirement.



F-14D Separation Testing of Mk 84 2,000 lb General Purpose Bombs

F-14A AIR-TO-GROUND HISTORY

The F-14A, while designed primarily as an air superiority platform, possesses a highly capable air-to-ground weapon delivery system. As reported in reference (a), this capability was highly tested in 1977 during which it was determined that several deficiencies existed with the BRU-24/25 suspension equipment illustrated carrying 14 MK 82 500 lb stores during an early test sortie in figure 1.



Figure 1
F-14A Carrying 14 MK80 Series 500 lb General Purpose Bombs

This unique configuration, i.e. fuselage vice pylon mounted weapons, proved to be adverse to free fall weapon separation. Specifically, the ejection force of these racks was inadequate for separating air-to-ground stores from the tunnel area between the engine nacelles, an area dominated by a flow field tending to hold the bombs in close proximity to the aircraft. While weapon separation was generally acceptable, the resulting instabilities induced bomb-to-bomb collisions unacceptable from a safety standpoint. While the air-to-ground effort was subsequently terminated and the capability to install the BRU-24/25 racks removed, the basic air-to-ground weapons control system remained.

F-14A STORE CARRIAGE/SEPARATION IN THE 90'S

The F-14A air-to-ground capability was resurrected in the late 1980's in response to demands for increased flexibility of carrier aircraft. To rectify the deficient separation characteristics, the BRU-32 bomb rack was adapted for use with the existing AIM-54 Phoenix air-to-air missile rail with a Navy designed and manufactured adapter unit. The buildup of carriage equipment is illustrated in figure 2.

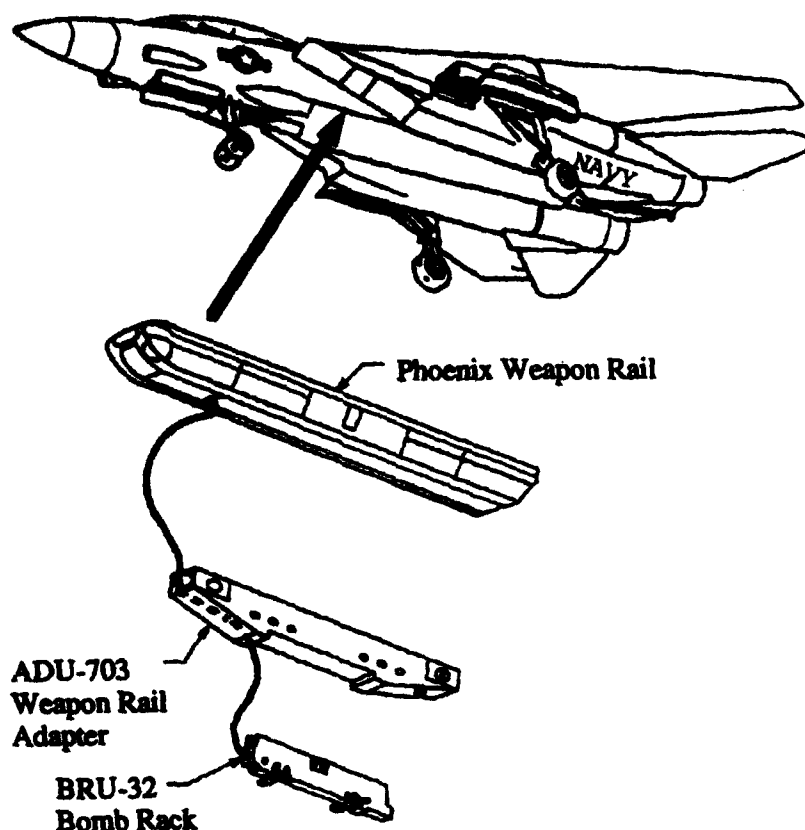


Figure 2
F-14 Air-to-Ground Suspension Equipment

Used as the parent bomb rack on the F/A-18 since its inception, the BRU-32 provided ample ejection force to safely separate up to four stores from the influence of the tunnel area. As of this writing, the F-14A has safely separated 500, 1,000, and 2,000 lb MK 80 series General Purpose Bombs (GPBs) through the transonic flight regime as well as the Navy's inventory of Cluster Bomb Units (CBUs). In support of the air-to-ground mission, separation testing has also been performed on LUU-2 night illumination paraflares, MK 58 Marine Location Markers (smokes), MK 76 practice bombs and Laser Guided Training Rounds. Testing of Tactical Air Launched Decoys (TALD) is ongoing. A full description of MK 80 series testing on the F-14A is presented in reference A.

F-14D STORE CERTIFICATION METHODOLOGY

The F-14D, introduced in 1990, incorporated an array of improvements including a MIL-STD 1553 digital data bus, four Multi-Function Displays, a digital radar display, improved HUD, a Hughes APG-71 radar, and an Infra-Red Search and Track Set (IRSTS). While structurally identical to the F-14A, the single outward difference in the F-14D is the Dual Chin Pod (DCP) which housed the IRSTS as well as the Television Camera Set (TCS). This necessitated additional weapon certification testing (both air-to-air and air-to-ground) to ensure no unsafe separation tendencies were introduced by the additional frontal area. For comparison, the F-14D DCP is illustrated with the F-14A single chin pod in figure 3.

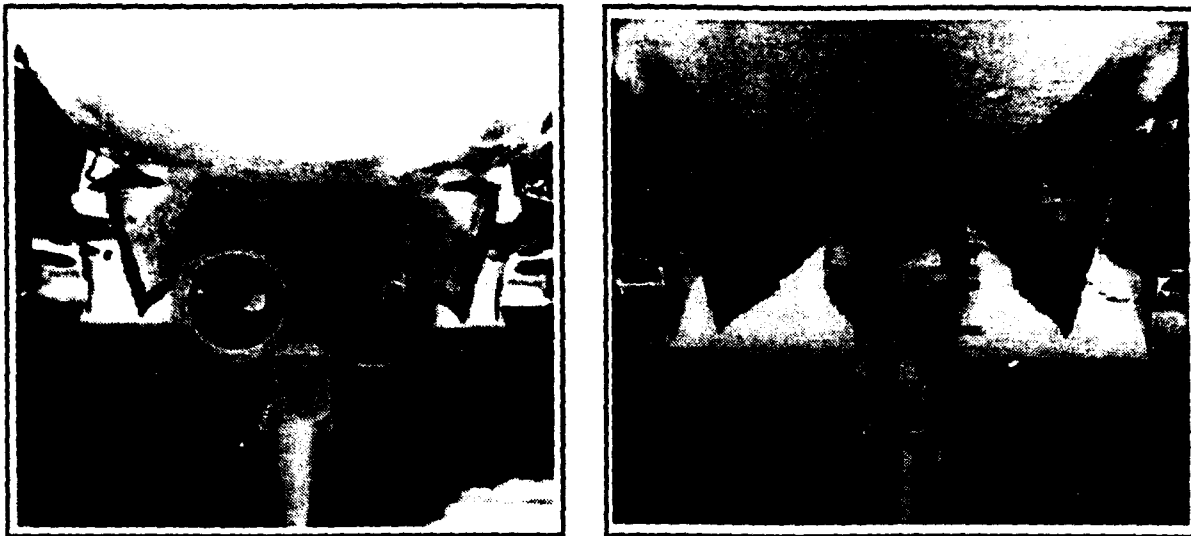


Figure 3
F-14D Dual and F-14A Single Chin Pods

Faced with the prospect of running parallel weapon certification programs on both Tomcat models, the Navy sought a method by which the scope of the F-14D effort could be reduced. Grumman Aircraft Corporation (GAC), the prime contractor for the F-14D, developed, in conjunction with the Navy's flight clearance authority, such a method which was eventually adopted for use. This technique utilized wind tunnel testing previously performed under an unrelated contract to derive predicted separations for MK 80 GPBs using the Influence Function Method (IFM). While prediction techniques have become commonplace for most weapon certification programs, the unique approach adopted for the F-14D involved using Navy supplied quantitative data from separation testing to validate contractor separation predictions by correlating them to flight test results. In this way, the contractor and the Navy hoped to refine and fully validate this prediction technique for use in follow-on multiple release and new store testing.

Correlation of the wind tunnel results required a method by which a precise time history of position and attitude of free-fall stores could be measured while the stores were within a defined volume of analysis beneath the aircraft. The Navy's flight clearance authority requested accuracies on the order of ± 4 in. for proper correlation. This volume, defined by the contractor and postulated to encompass the local flow field of the F-14D was identified and is illustrated in figure 4.

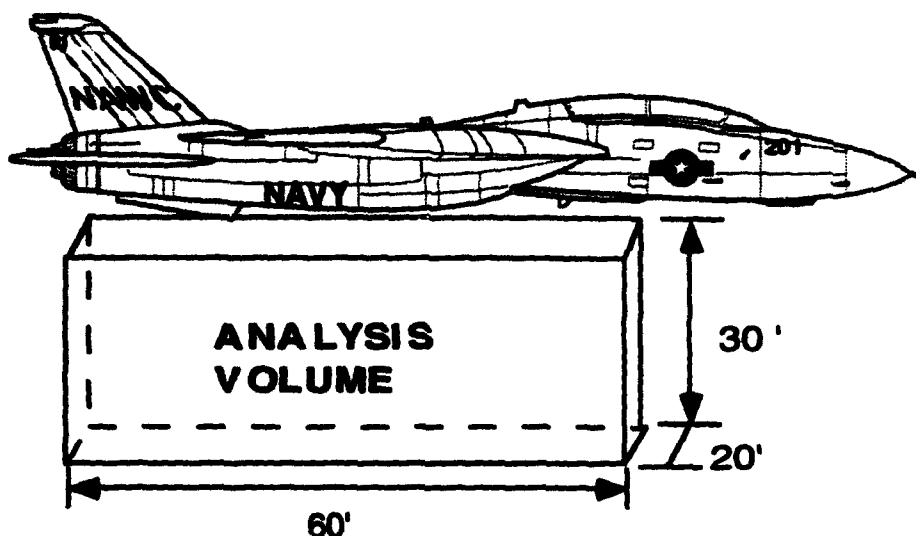


Figure 4
F-14D Analysis Volume

There were two options available which would provide this degree of accuracy; six degree of freedom (6-DOF) inertial packages and photogrammetry. The Air Force PDAS system was briefly considered but eliminated due to questions over its ability to provide the requisite accuracy. While 6-DOF inertial packages installed in the electrical fuze well of GPBs were deemed better from a data analysis/reduction standpoint, the disadvantages were numerous. For example, the package accelerometers had to be carefully chosen for the motion expected from the weapon. If too sensitive the weapon motion might saturate it and exceed its limits, and, if not sensitive enough, there would not be enough resolution for accuracy. By far though, the biggest disadvantage with an on-board instrumentation system was the cost associated with purchasing an instrumentation package for every weapon to be tested. Depending upon the quality and complexity of the system, the costs could easily exceed the program budget.

As another option, the Naval Air Warfare Center-Aircraft Division (NAWC-AD) had recent experience with photogrammetry for obtaining quantitative data from weapon separation. Most recently, a photogrammetric triangulation technique was used to quantify the spatial position and orientation of an AIM-9 Sidewinder jettison from the pylon station of an F/A-18 (reference C). This technique used the multi-camera solution described in detail in a following section. While the survey techniques for this particular test program were, by today's standards, crude and consequently, the accuracy of the results questionable, it provided a much needed boost to the photogrammetric capability at NAWC-AD as well as a sound foundation for follow-on photogrammetric programs. Given the recent advances in this capability at NAWC-AD and number of air-to-ground stores to be analyzed (45 total), photogrammetry was selected for the F-14D.

Upon selecting the analysis method, a matrix of test points was agreed upon by the contractor and the Navy consisting of fifteen flights during each of which three stores would be released. The store stations under consideration were the two front stations nearest the DCP (stations three and six) and station five, the station directly aft of station six. It was anticipated that the stores

behind the flat portion of the DCP (stations five and six) would be most affected by the DCP. Station three was tested to retain the normal release sequence of 4-5-3-6. The F-14 station numbering sequence is illustrated in figure 5.

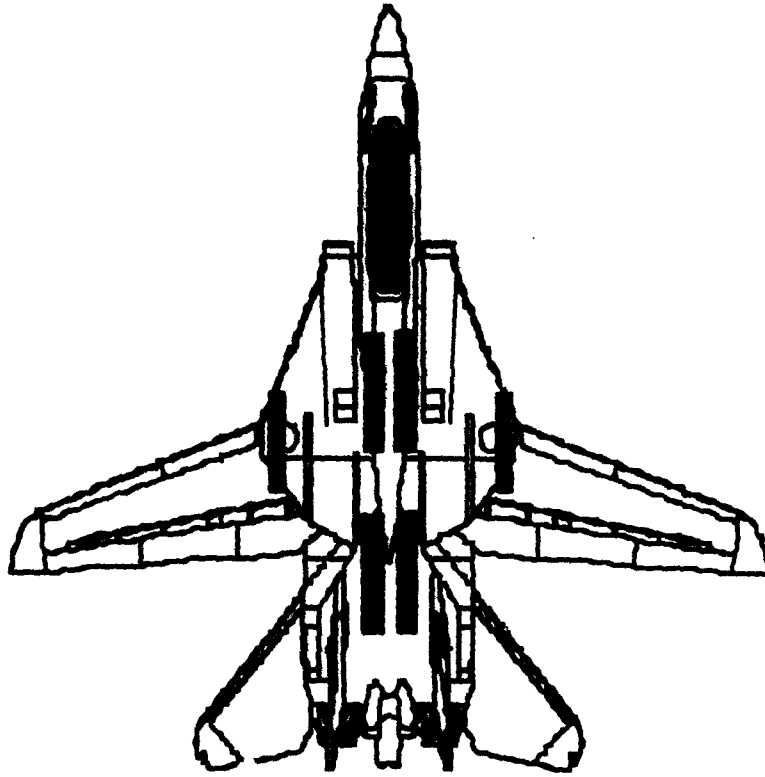


Figure 5
F-14 Store Stations

While most of the MK 80 GPBs were tested, concentration was on the 500 lb. MK82/BSU-86/B to which ten flights were dedicated; nine in the low drag configuration and one high drag. Illustrated in figure 6, the MK82 bomb body with the BSU-86/B tailfin is generally accepted to be a very stable store. Released from the F-14A, however, it exhibited other than ideal pitch and yaw motion.

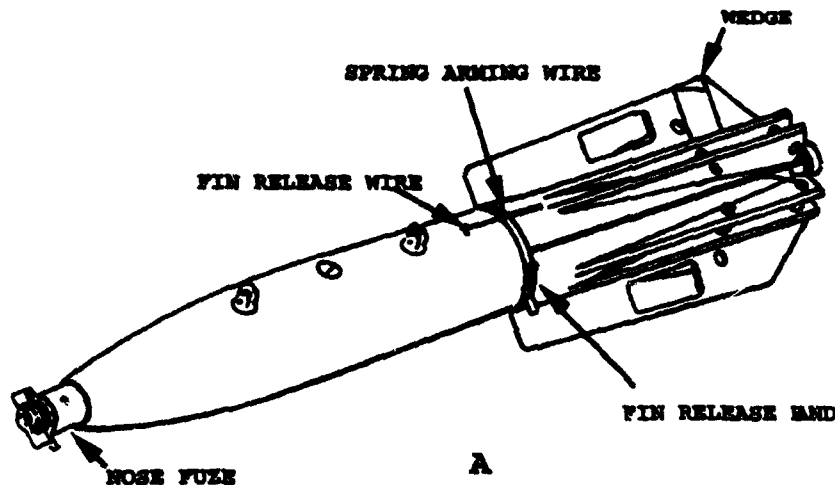


Figure 6
MK 82/BSU-86/B GPB (Low Drag Configuration)

It was thought that correlation of this particular weapon with the IFM predictions would naturally result in satisfactory predictions for the other MK 80 GPBs. Only one flight of three bombs each was planned using the remaining MK 80 stores with these used exclusively as a spot check of the correlation obtained with the MK 82/BSU-86/B. All bombs were released from within the following flight conditions:

Dive angle	0 to -60 degrees
Airspeed	500 to 600 KCAS
Mach	0.8 to 1.07 TMN

Prior to delving into the specifics of the flight test, analysis and results a general description of the photogrammetric method as applied to airborne weapon separation will be presented.

PHOTOGRAMMETRY, A GENERAL DESCRIPTION

Photogrammetrics is the study of obtaining measurements from photographs. Applied to weapon testing, it is used to quantify a weapon's displacement and attitude after it has been released or launched from an aircraft. Such information is typically used to validate the accuracy of a prediction or to determine if the characteristics are "safe" enough to proceed to more severe release conditions. Traditionally, information about weapon separation has been obtained qualitatively from high speed cameras mounted either on permanent platforms integral to the aircraft or on 'hardbacks' affixed to existing bomb racks.

These high speed cameras are also adaptable for photogrammetry. To accomplish this type of analysis, several calibrations of the test equipment must be performed to quantify such details as camera location, lens aberrations, etc. A block diagram of the process is illustrated in figure 7.

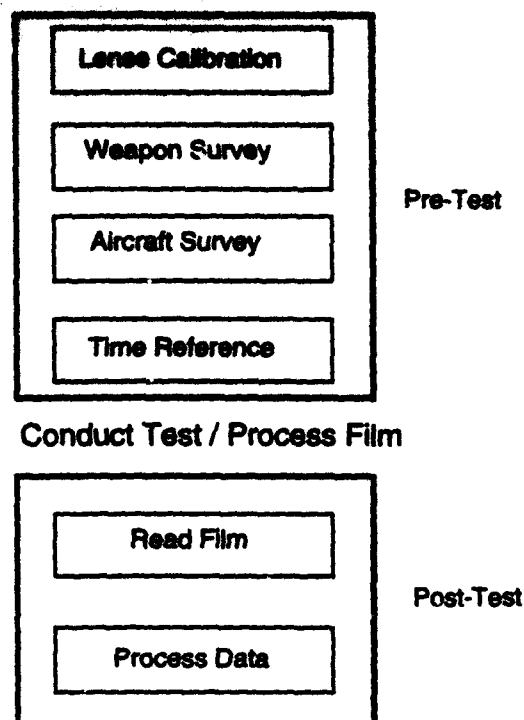


Figure 7
Photogrammetric Process Block Diagram

As shown, there are pre- and post-test operations. While most of the pre-test methodologies are common, the post-test requirements can vary depending upon the type of test or the camera solution chosen. Various solution techniques are available including single, dual, and multi-camera; the selection of which depends upon the accuracy of the data required and the complexity of the computer algorithm available to reduce the data. For these tests, a multi-camera solution was applied and the discussions presented in this paper are limited to this method.

At the heart of the analysis lies the high speed cameras themselves. For this application motion was recorded on high quality ASA 400 16mm film using Photosonics Model IPL high speed cinematic cameras operating at 200 frames per second. Each camera accommodates up to 250 ft of film providing up to 45 seconds of footage when operated at .005 seconds per frame. For weapon separation photography, 5.9 mm lenses are typically installed. This same focal length is also aptly suited for photogrammetric analysis.

A first priority is calibration of the camera lenses. This simply maps out any distortion in the lens (ex: pin-cushion or barrel) and determines how the projection of the object's image on the camera film frame (or film plane) is affected. Lens calibrations are performed by aiming the camera at a calibrated target, usually a plane surface like a 4 ft X 8 ft ply-board with graduated gridwork painted on it, and running several frames of film. The results of this calibration are entered into the algorithm so that distortions are taken into consideration when reducing film data.

In addition to the lens calibration the objects, in this case the aircraft and weapons, have to be "targeted". Targets are easily identified points (either

integral to the object or placed on the object) at known positions with respect to a coordinate system. The coordinate system for the aircraft was the standard coordinate system including water line, butt line, and fuselage station. While only three targets are required for a photogrammetric solution, many targets are usually affixed to ensure that the minimum number will be available. It is imperative that the targets be visible by as many cameras as possible. A typical aircraft targeting scheme is illustrated in figure 8.

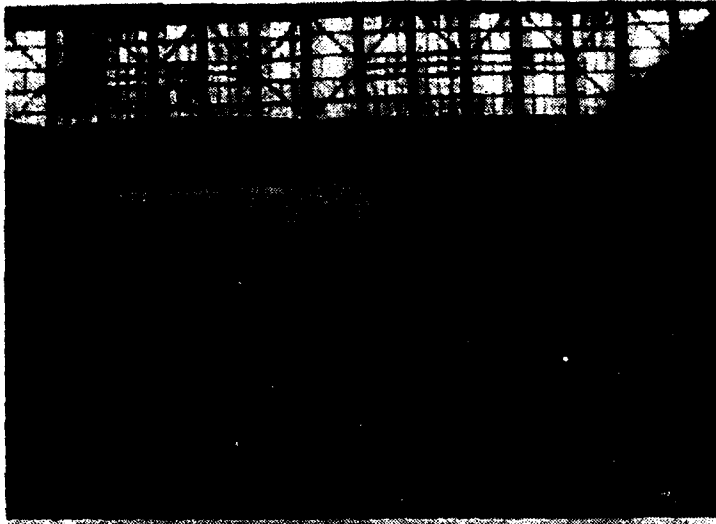


Figure 8
F-14 Aircraft with Photogrammetric Targets

Weapons are targeted with respect to their center of gravity. As opposed to individual targets, a ring targeting scheme is well suited for axisymmetric stores such as general purpose bombs. The ring creates a "virtual target" at its center which is interpreted by the individual reading the film. While this expedites the survey and preparation of bombs, the potential for error is introduced by giving the film reader the liberty to interpolate the position of the virtual center. This method also prohibits the extraction of roll data which is inconsequential for this analysis. Figure 9 illustrates the ring targeting method.

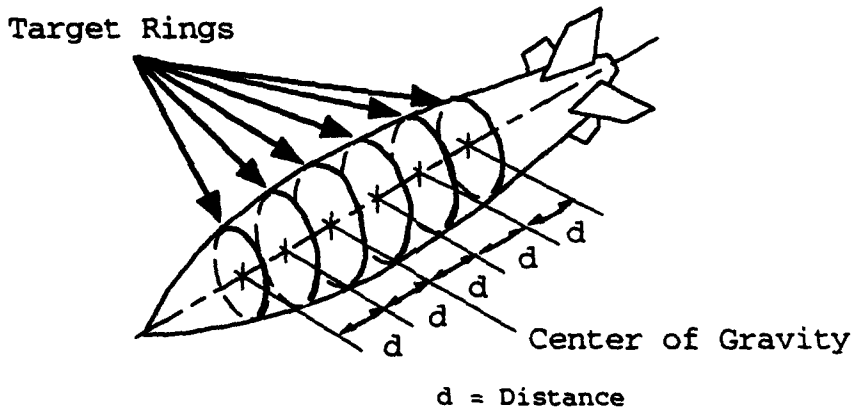


Figure 9
Bomb with Photogrammetric Targets

With the lens calibration complete, the cameras are mounted on the aircraft and the survey performed. For this, a precision surveyor's transit is used to define the coordinates all aircraft targets, weapon racks, and camera film planes in the aircraft coordinate system. While a tedious process, the survey is crucial to the ultimate accuracy of the spatial data. In addition to fixing the position of the camera's film plane, an initial orientation of the camera is obtained. This orientation, or direction the camera is pointed with respect to the axes of the aircraft, will be used as initialization data in an iterative computer algorithm to determine precise camera orientation for photogrammetric analysis and is depicted in figure 10.

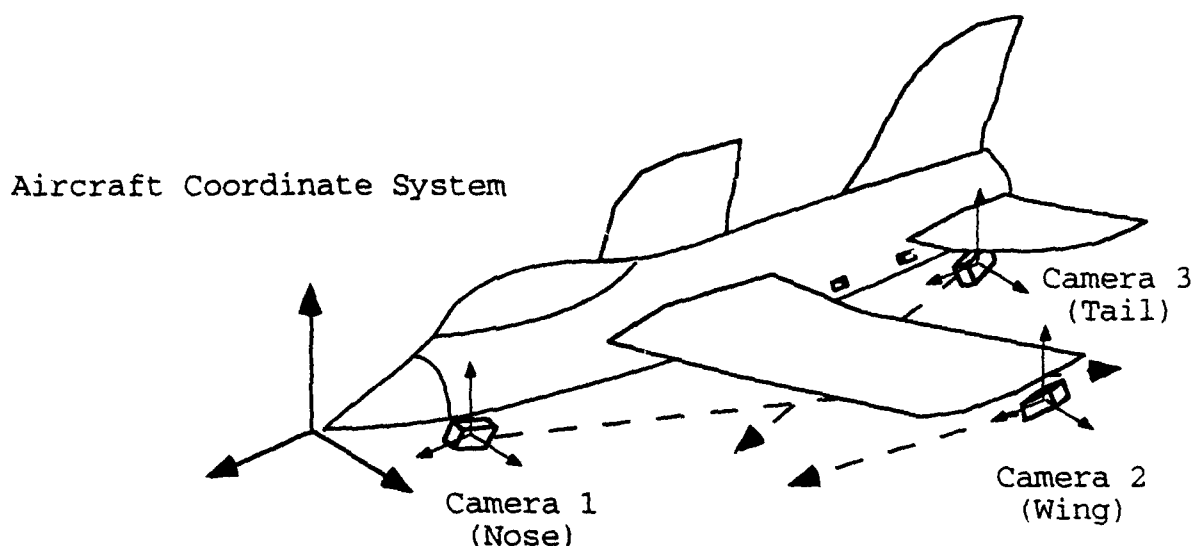


Figure 10
Camera Location and Orientation

Also instrumental in the accuracy of the data, is the method by which the film frames from all cameras are synchronized during the film reading process. This can be accomplished with a simple flash bulb set off at the instant of first bomb motion or by using a precise, common time reference such as the IRIG (Inter-Range Instrumentation Group) system extensively employed in a variety of flight testing. 'IRIG' time is digitally encoded on each film frame of each camera so that the precise reference time is available within 1/1000 sec during the film reading process. A complex system to synchronize the shutters of each camera is also available if extreme precision is required.

With the pre-test operations complete, flight testing is ready to commence. During a typical weapon release, as the bomb falls from the aircraft, its image is recorded on a frame of film every 0.005 seconds as shown in figure 11. At the conclusion of the flight the film is developed and "read" by a special film reader such as the TELEREADDEX 29E semi-automatic film reader and digitizer used at NAWC-AD. These machines project an image onto a

two dimensional surface and are designed for precise and fast measurement of X and Y coordinates (2-D) from filmed data.

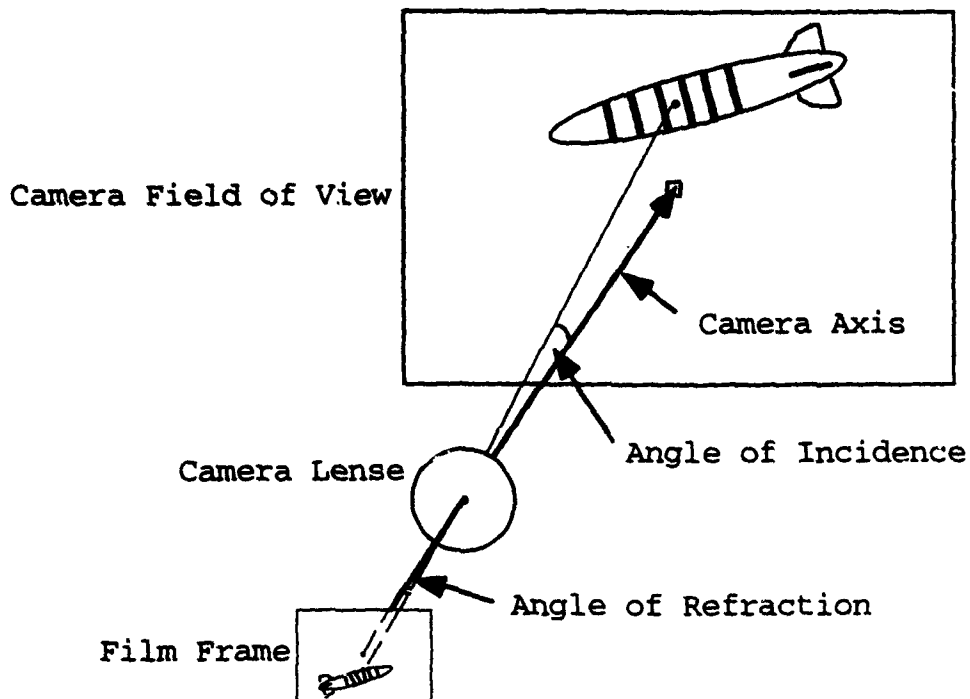


Figure 11
Projection of Bomb Image on Film

The reading system converts the measurements, made on the projected image, into digital values which are then passed to an automatic recorder. Distances are measured along two orthogonal axes by manually positioning vertical and horizontal 0.007-in. diameter crosswires so that their point of intersection coincides with the point on the image at which the coordinated reading is to be taken. This process creates a data set for all of the targets in every frame of film and is illustrated in figure 12.

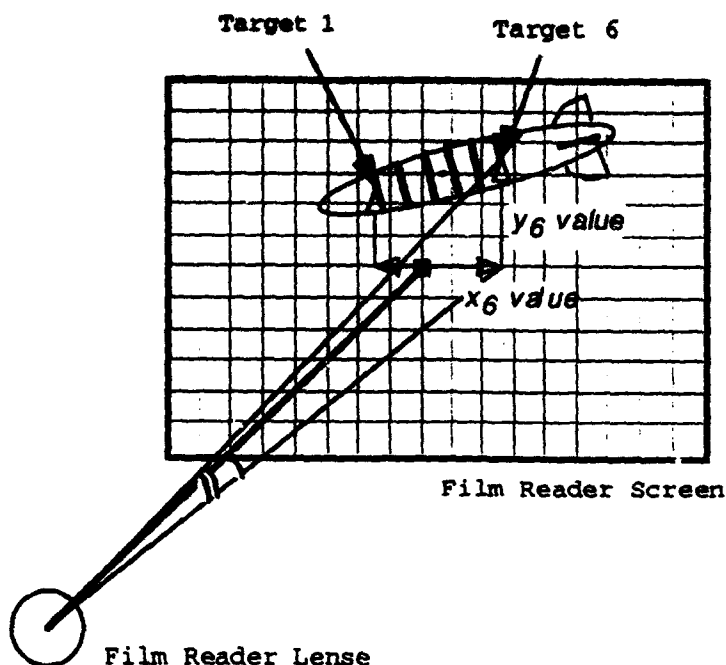


Figure 12
Process of Reading Film

At this point the location of the film plane, the camera axis orientation and the target's image position in the film plane are known. By applying Snell's law and compensating for the known lens distortion, a vector can be established from the film plane through the lens to the weapon target. If two or more cameras of known position have vectors from their film plane to the same target at the same instant in time, triangulation can be used to determine the target's position in the aircraft coordinate system (figure 13). Once all the weapon's virtual target positions are known for each frame, a mathematical model of the weapon can be fitted to the position of the targets. This requires an iterative process, moving the weapon and changing its attitude until a match is found.

Several of the lessons learned from the F/A-18 Sidewinder Jettison program were incorporated to offset some of the labor intensive and complicated tasks associated with the pre-test calibrations. Specifically, a more accurate and less time consuming method of surveying the aircraft was required. To aid in the aircraft survey, a Sokkia NET-2 infrared laser transit was employed which used retroreflective targets to calculate distances to within 1 mm, and azimuth and elevation to within 2 seconds of arc. The transit readings were entered directly into a computer which fixed the position of the surveyed point in the aircraft coordinate system real time. This replaced the standard survey equipment all but eliminating the possibility of human error.

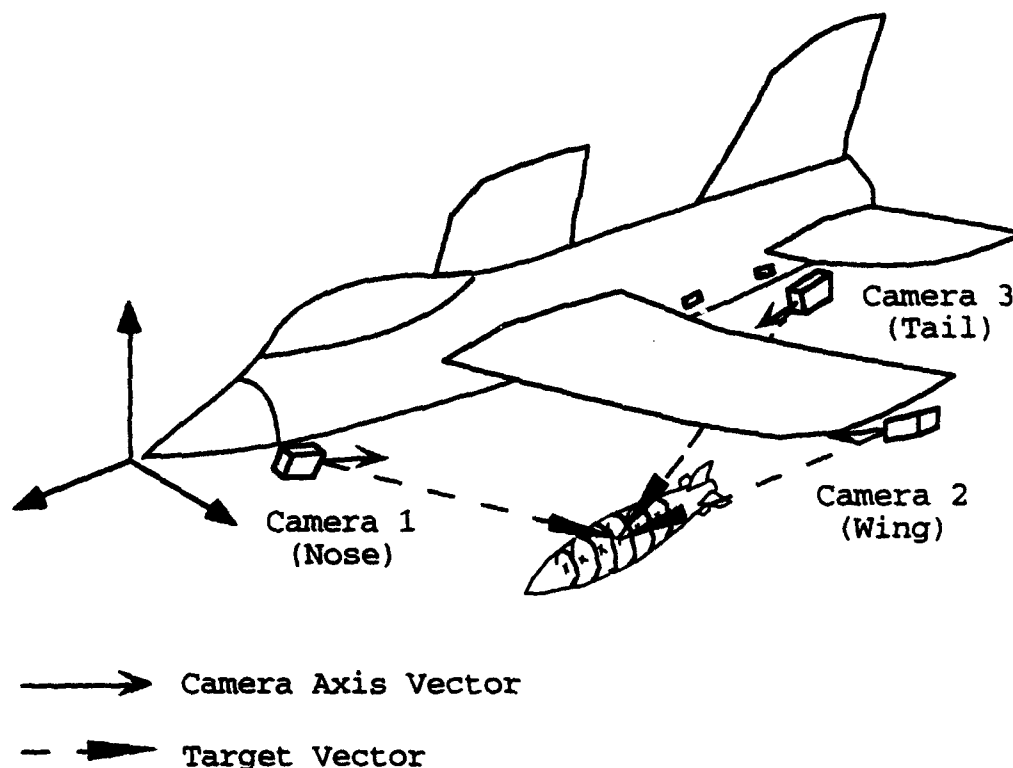


Figure 13
Multi-Camera Coverage for Photogrammetric Solution

To improve the time reference, a centralized time code generator was used for these tests. As previously mentioned, IRIG time was digitally encoded directly on the film frame. Typically, the time source on each camera would be time synchronized at the beginning of a flight. Over the course of a flight, however, they may drift apart ever so slightly degrading the quality of the solution. By using a centralized time code generator all cameras were assured of displaying identical time for the duration of the flight.

PHOTOGRAMMETRICS APPLIED TO THE F-14D

Several technical challenges were associated with the adaptation of photogrammetric store separation to the F-14D not the least of which was obtaining the requisite camera coverage of the analysis volume beneath the aircraft. Thus far, all F-14A weapon separation testing was conducted using a total of seven high speed cameras. Since the accuracy of the triangulated solution depended upon the base length of the triangle i.e. the distance between the cameras, additional, more extensive camera coverage was required.

For this purpose wing tip camera pods, developed by GAC for earlier-air to-air weapon tests, were installed. These pods were essentially 'off the shelf' and were able to accommodate the IPL cameras used in this test. In addition to the wing tip cameras, camera hardbacks and four more IPL cameras were installed on the multi-purpose pylon for a total of 13 high speed, cinematic cameras. A comparison of the 'old' F-14A camera configuration with the 'new'

F-14D configuration is presented in figure 14. With 5.9 mm lenses installed in the wing tip cameras, coverage to 35 feet beneath the aircraft was obtained. This compared favorably with the 30 feet desired by the contractor.

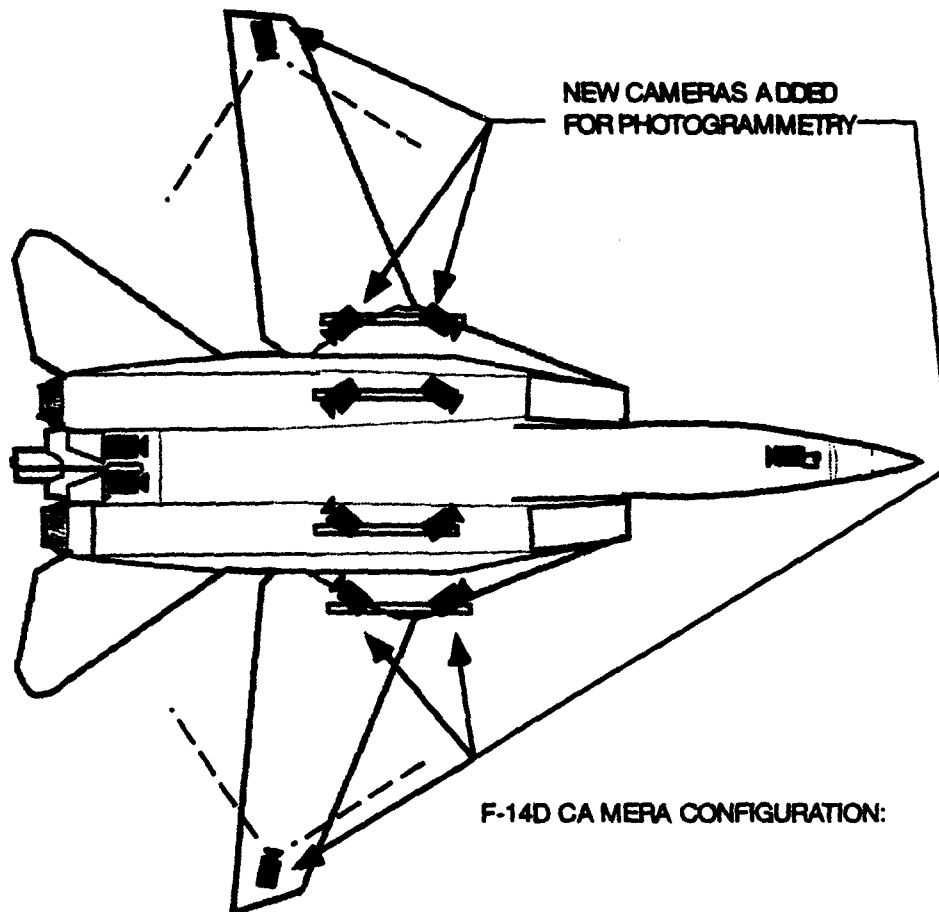


Figure 14
F-14A High Speed Camera Configuration

While the addition of wing tip cameras generously expanded the coverage volume, the variable sweep of the wing and pronounced vibration of the wing tip during high speed runs complicated the photogrammetric solution. Wingsweep angle was controlled automatically as a function of Mach and altitude. During dive deliveries these parameters and consequently the wing sweep angle and camera perspective continuously changed. To compensate for this motion a 'real time' orientation of the camera was required for each film frame. To accomplish this the targets on the side of the aircraft were used to obtain a photogrammetric solution for the camera itself in each frame as illustrated in figure 15. The geometric solution essentially requires three known, non co-linear points to be in the film frame. This illustration, made from an actual film frame, depicts the process by which the targets, hence orientation, is determined.

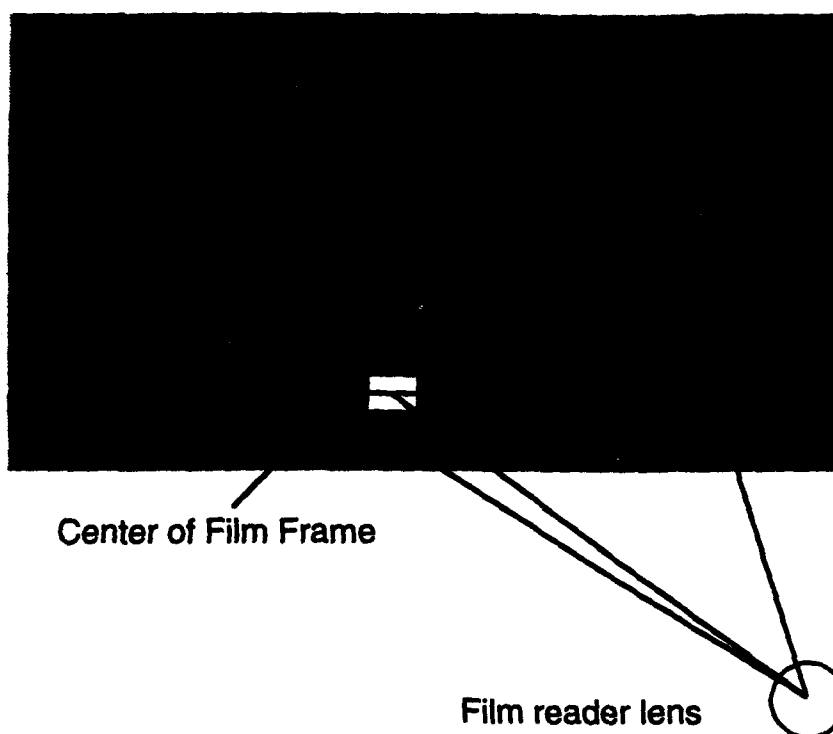


Figure 15
Wing tip camera triangulation

As mentioned, NAWC-AD used an iterative algorithm to determine precise camera orientation using the field survey of the aircraft for initialization data. This algorithm was able to fix the position and orientation (x, y, z, pitch, roll, yaw) of a camera provided enough surveyed targets on the aircraft were visible in the film frame. For each of the aircraft-mounted cameras x, y, and z position was held fixed because it was theorized that these parameters would not vary much from those obtained from the field survey. Camera pitch, roll and yaw were allowed to vary in the iteration to precisely fix the orientation. Two aircraft targets had to be in the film frame to complete this fuselage camera orientation.

For the wing tip cameras, x and y were fixed with z allowed to vary in addition to pitch, roll and yaw. The z variable was allowed to vary to compensate for the up and down movement of the wing tip due to airloads. To converge on a solution with this extra degree of freedom, an additional fuselage target (total of three) had to be in the film frame. To fix the x and y variables for these cameras the location of the film frame had to be determined as a function of wingsweep angle. This was achieved during the ground aircraft survey when the wings were swept and surveyed in five degree increments. Wingsweep angle was an instrumented parameter so this provided the x and y position of the camera within ± 1 in. While the orientation of the wing tip camera may have been determined without the use of the wingsweep instrumentation (i.e. allowing all six variables: x, y, z, pitch, roll, and yaw to vary) this expedited the iteration resulting in a quicker solution. Once the wing tip camera was precisely oriented it, in turn, could be used in combination with other cameras to precisely locate the weapons.

In addition to wing tip camera position another technical hurdle was satisfactorily determining the accuracy of the photogrammetric solution. The precision of these solutions had been speculated since there existed several sources of error and, during live weapon releases, there was no 'truth data' to which the solution could be compared. Accuracy was dependent upon several factors and in many cases the errors were additive. For example, a few milliradian error in the aircraft survey may translate into a several inch error in the final product. Error sources included but were not limited to:

- Angular survey measurement
- Range survey measurement
- Film reading / virtual target interpretation
- Lens calibration
- Phase lock / film frame interpolation
- Camera motion

To isolate all but the camera motion error, a ground test was performed prior to the first flight. For this test the fully surveyed and targeted aircraft was raised on aircraft jacks and the landing gear retracted. This provided the maximum availability of the analysis volume. A painted and targeted bomb was then moved to several locations under the aircraft to simulate the actual path the store may follow as it separated. This ground test is depicted in figure 16.

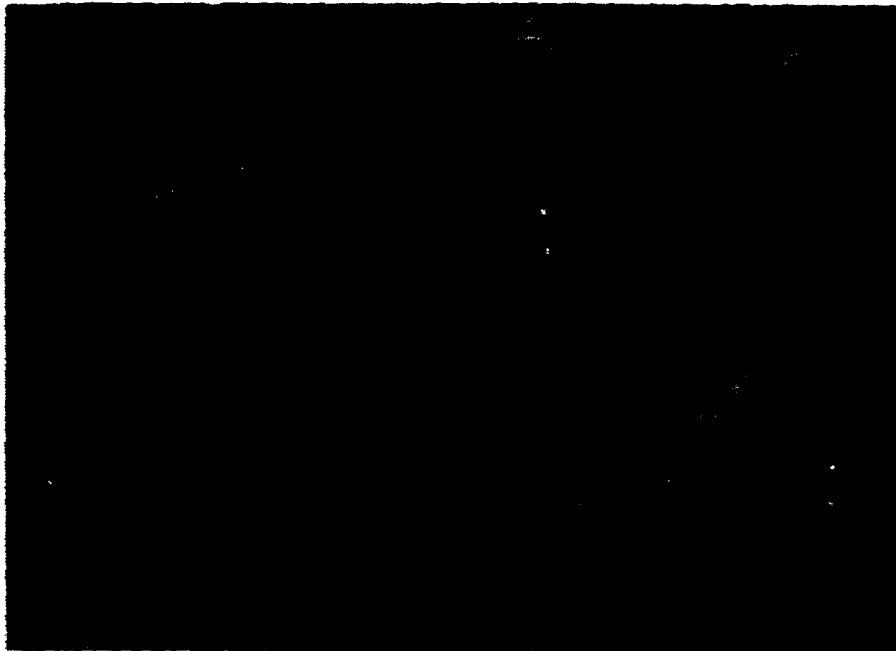


Figure 16
F-14D Photogrammetric Ground Test

In each position, the bomb was surveyed in the aircraft coordinated system to obtain truth data and the cameras were run for several frames. The film data was then reduced and the photogrammetric accuracy compared to the surveyed truth data. Results were encouraging with an accuracy of 3.28 inches with the bombs in a simulated carriage position, improving to 2.8 inches approximately 2 ft below the aircraft and degrading linearly below that.

While camera vibration/motion was not able to be simulated in the ground test (aside from sweeping the wings) a provision was made to compensate for this condition should it occur. This will be discussed in the next section. As an additional independent verification of the accuracy of the photogrammetric solution, a 6-DOF inertial package was released in a MK 83 bomb approximately mid way through the program. The results of this release are presented in a following section.

In addition to the technical challenges associated with this program, several logistical difficulties were anticipated as well. The effect upon the camera survey of repeated touch and go landings, especially the Navy variety, was unknown. The same held true for the removal and re-installation of the camera hardbacks. While the cameras were physically locked onto the camera mount and hardback, the effect of even a minor adjustment of a sway brace while the cameras were removed was unknown. For this reason, the aircraft was put under a 'project flight only' status for the duration of the program. Since there were three days allocated for data reduction following a flight, the resulting aircraft utilization rate was poor.

Problems were also experienced during scheduled maintenance. Navy aircraft were on a 14 day wash schedule. While initially permitted to do 'dry washes' where the aircraft is cleaned with spray solvents, wet washed had to be resumed mid way through the program for instruction compliance. This resulted in a lengthy process by which each camera was waterproofed prior to each wash. Scheduled maintenance on the ejector racks which suspended the camera hardbacks also presented a problem in that the sway bracing had to be marked in position to prevent compromising the survey during removal.

FLIGHT TEST

Flight testing commenced 21 May 1993 and concluded 7 September 1993. During this period 17 flights for analysis were flown during which 49 single bomb release events occurred. Photogrammetric solutions for 47 of these 49 releases were obtained. One of the bombs released contained an experimental 6-DOF telemetry package. Forty-five of the 49 events had at least a three camera solution.

While the program proceeded without any major difficulties some unanticipated problems did arise. First was the deflection of the forward cameras on aircraft stations 2 and 7 camera hardbacks. The design of the camera hardback sway braces and mounts positioned the cameras out on a cantilevered and unsupported end of the hardback. At the high dynamic pressure test points the airloads on the camera induced a film plane deflection of approximately 1/2 inch which compromised the photogrammetric data. The station 2/7 camera hardback is illustrated in figure 17.

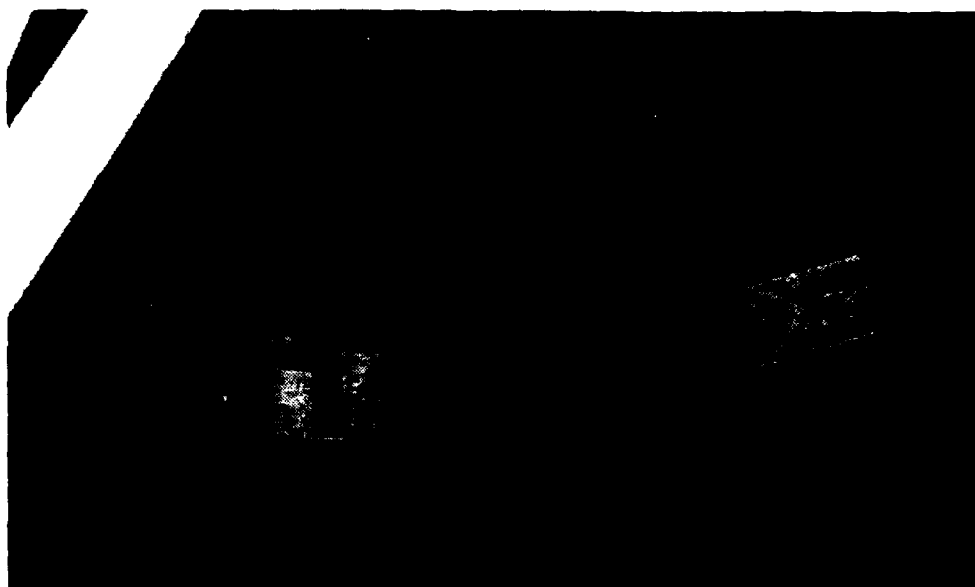


Figure 17
F-14D Station 2/7 camera hardback

To compensate for this deflection, a 'real time' orientation of the affected cameras was performed just prior to weapon release. Recall that for precise fuselage camera orientation, x, y and z were assumed to remain fixed in the aircraft coordinate system. This deflection was akin to movement in the z direction and had to be accounted for. As was described for the wing tip cameras, the z variable was allowed to vary in addition to pitch, roll and yaw for these affected fuselage cameras producing an accurate solution in the iteration. As opposed to performing orientation for each film frame, it was done once per bomb release with the assumption that the deflection remained constant while the bomb was within the field of view of the affected camera.

Additional difficulties experienced during the flight test, conducted during an exceptionally humid summer, was limited visibility and bomb obscuration by vapor trails. Even though, in most cases, the bombs were no more that 30-40 feet from the camera, the condensation of moisture about the engine nacelles obstructed some targets from sight. Surface weather observations obtained for each flight date indicated that better film reading quality corresponded to lower temperatures, dew points, and humidity. While film quality deteriorated in August and September sortie rate remained consistent with that obtained in the late Spring with the impact to the program limited only to the quality of the photogrammetric data. Mostly affected by the vapor trails were the wing tip cameras.

Compounding the vapor trails was the paint scheme selected for the weapons. Completely unrelated to the photogrammetric effort but being conducted concurrently, a ballistic analysis was being performed on the released stores. A paint scheme tailored for good visibility from the ground based high speed cameras was desired and a bright orange was selected. Unfortunately, this color was not well suited for photogrammetric film reading and accuracy was probably somewhat degraded. (The white tape on a blue bomb scheme, used when ballistic testing was not scheduled, performed satisfactorily and was more desired than the green-on-orange used otherwise).

Bomb visibility was also highly dependent upon the time of day of the flight. Flights conducted later in the afternoon were susceptible to an intense glare from several of the cameras.

DATA REDUCTION AND PROCESSING

Since the test aircraft was limited to "project only" flights it was important that data turnaround be completed in a timely fashion. Consequently, post-test activities were limited to a seventy-two hour period. This three-day period was allocated to read and reduce the approximately 12,000 data points that resulted from each flight. Figure 18 illustrates the necessary post flight steps.

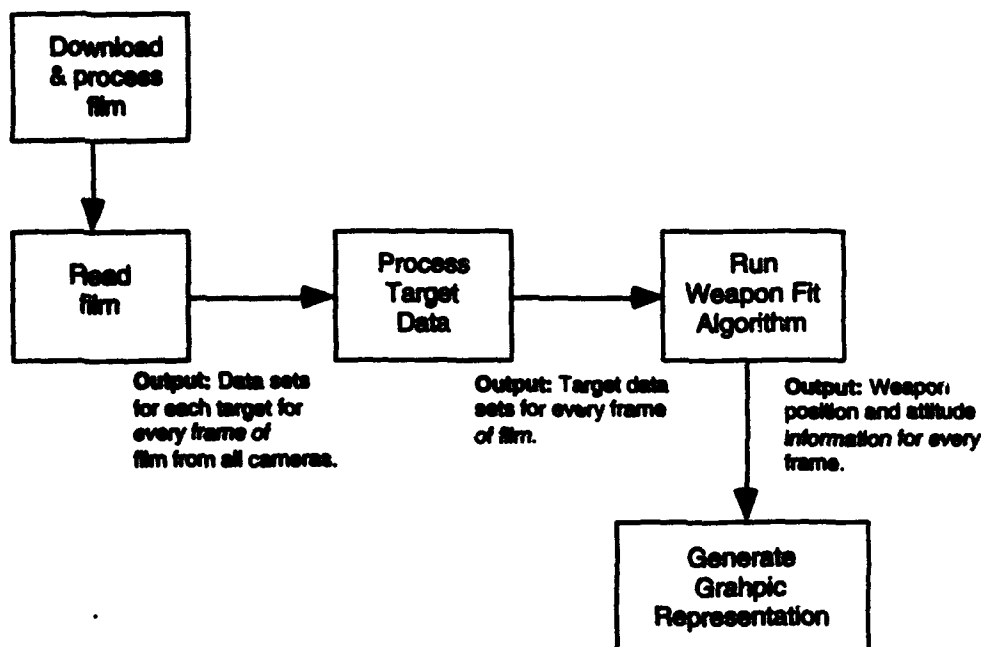


Figure 18
Photogrammetric Analysis Process

An example of the resulting photogrammetric data is presented in Appendix A. Some peculiarities in the data were noted. One such anomaly was the abrupt discontinuity in pitch data shown in figure 19.

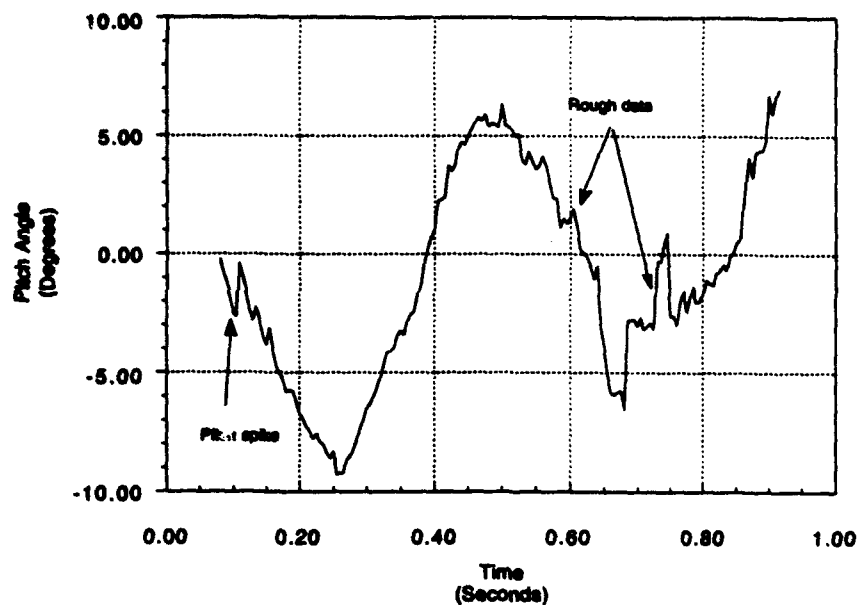


Figure 19
Spikes and Roughness of Photogrammetric Data

An additional observation is the roughness in the data which occurred when the quality of the film coverage was degraded or there was a camera failure. Another problem occurred with when the bomb fell out of the field of view of the station 1/8 cameras. At this point only the wing tip cameras were providing coverage and the transition caused a spike in the data as shown in figure 20. This characteristic was observed throughout the test program.

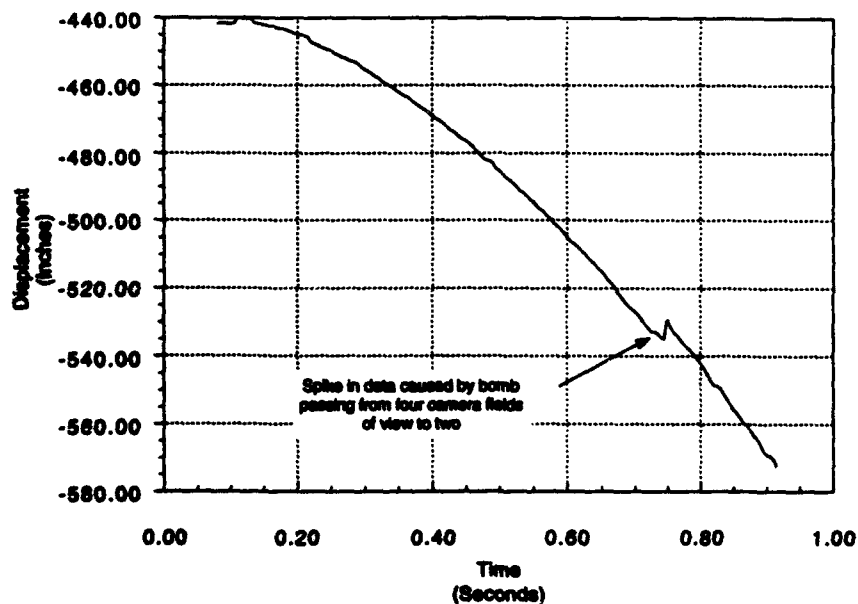


Figure 20
Data Error Caused by Changing Camera Coverage

Recall that the purpose of the test program was to validate wind tunnel predictions and to determine a safe separation envelope. As the final portion of the data analysis, the photogrammetric results were compared to the wind tunnel predictions. While NAWC-AD only performed a qualitative comparison, the tabular data defining the state vector of all 47 bombs was forwarded to GAC for full correlation. A representative comparison is presented in figure 21. In this particular instance it is apparent that the actual pitch amplitude was smaller and the frequency was higher than the prediction. From the figure one can visualize how, through manipulation of the aerodynamic coefficients, the predicted data was eventually to be correlated with the actual results.

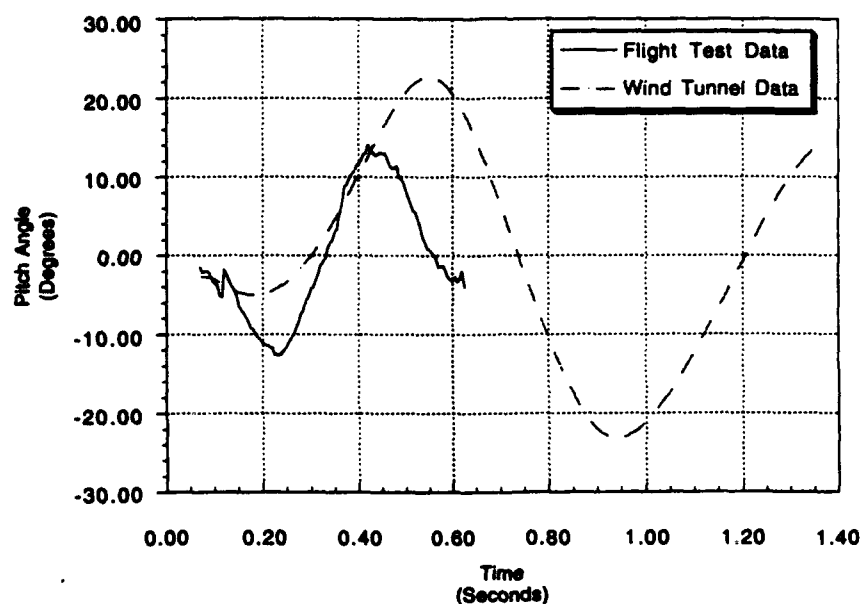


Figure 21
Comparison of Actual vs. Predicted Data

At one point in the test program the opportunity was available to use an weapon instrumented with a 6-DOF inertial package for comparison/validation with the photogrammetric solution. This weapon was a MK 83 with a standard conical fin. Instrumentation consisted of ± 30 g accelerometers in all axes and ± 200 degree per second rate gyros. The 6-DOF data from the release is shown in comparison to the photogrammetric solution from the same weapon release in figure 22. Aside from an initial discontinuity in the photogrammetric solution, the comparison is favorable.

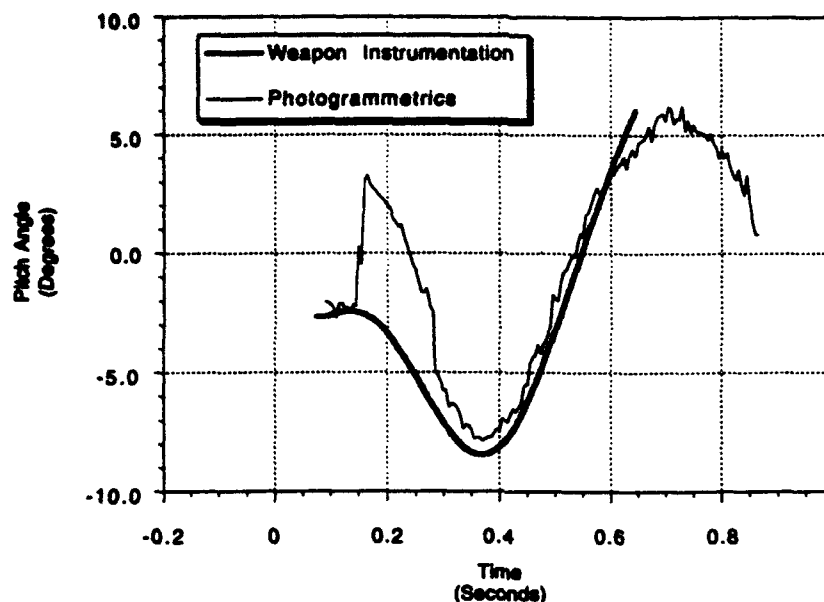


Figure 22
Comparison of Bomb Pitch Data

FUTURE RECOMMENDATIONS/LESSONS LEARNED

While at times a convoluted and complicated program to plan and execute, there were several lessons learned which may be adopted for similar photogrammetric efforts in the future. A summary of these is provided below:

(1) The benefits of the Sokkia NET-2 infrared laser transit, rented specifically to conduct the survey for this program, cannot be over emphasized. Not only did this instrument greatly simplify the aircraft survey but it improved its overall accuracy by 'an order of magnitude' as paraphrased from the leading engineer on the photogrammetric data reduction team. So impressed by this instrument was the survey team, that the NAWC-AD section responsible for conducting these tests eventually purchased one. (List price approximately \$50,000).

(2) Film turnaround time. As previously mentioned, the film reading process is very tedious and labor intensive. This drove up the turn around time i.e. time from the flight to the receipt of reduced data to 72 hours. For test plans that are conducted in series where subsequent points are contingent upon receipt of reduced data from a previous flight, this may cause delays as was the case for this particular program. To quantify the magnitude of the film reading effort there were an average of 4,295 manually read data points per bomb drop and an average of 11,876 data points per flight. Over 201,000 total data points were read over the course of the program from over 33,000 frames of film. Altogether, the program consumed 50,000 feet of high speed film.

As the statistics indicate, human error is readily introduced into the data reduction process. To alleviate this, a prototype of the workstation-based Semi-Automated Film and Video Reader (SAVFR) which performs digital analysis of

16 mm film and video is currently being evaluated at NAWC-AD. SAVFR, tailored specifically for flight test and analysis applications, was designed to introduce automation and artificial intelligence to increase the speed of the film reading process and improve the quality of tracking information.

(3) Although not addressed previously, the benefit of the widely spaced wing tip cameras was not realized. While one would believe that more camera coverage is better, the distances involved and the wide angle lenses used to get the requisite coverage degraded the accuracy of the solution. One can imagine how difficult it was for the film readers to pinpoint the center of the target rings when the target rings themselves became a blur on the film frame.

Along this same line, more in-depth planning to orient the cameras for maximum coverage would have been beneficial. While limited to specific aircraft locations, the cameras were moveable +/- 180 degrees in azimuth and down to -75 degrees in elevation. During the planning process this particular issue was not given sufficient attention and maximum utility was not obtained from each camera.

(5) Bomb preparation required an inordinate amount of time. As requested by the photogrammetric analysis group, the bombs were all surveyed and taped relative to the weapon center of gravity. While the mass properties of test ordnance is typically obtained as a matter of course, taping in reference to the c.g. was time consuming. A better technique would be to tape the bomb in reference to the weapon leading edge and measure the leading edge in reference to the c.g. For future applications NAWC-AD is evaluating the PIXSYS system developed for the U.S. Air Force, which uses near-infrared technology to produce accurate 3-D surveys of relatively small objects like stores. This should greatly reduce the survey and preparation time for stores.

Tape was used to form the rings on the bombs. While painting the rings seemed like the logical choice, there were several drawbacks to this method including the construction of a complicated painting jig. Unfortunately, the tape on the forward half of the bombs had a tendency to peel off. Although more difficult, painting is the preferred method and should be considered in the future.

Colorizing the bombs was also an issue. For ballistic visibility the bombs were painted orange. This, unfortunately, was not well distinguishable in the summer haze. A better and easier method was to leave the bombs their factory blue color and use white tape. The white-on-blue provided more contrast and enabled the acquisition of higher quality data.

(6) Finally, a more rigid hardback is recommended. This would make practical sense in that higher quality data would be obtained but also makes sense from a safety standpoint.

CONCLUSION

While adapted here to airborne weapon separation, photogrammetry has far reaching applications. As an example, the National Geographic Society and the Navigation Foundation recently teamed up to prove, via photogrammetric analysis of prints taken during his expedition, that ADM

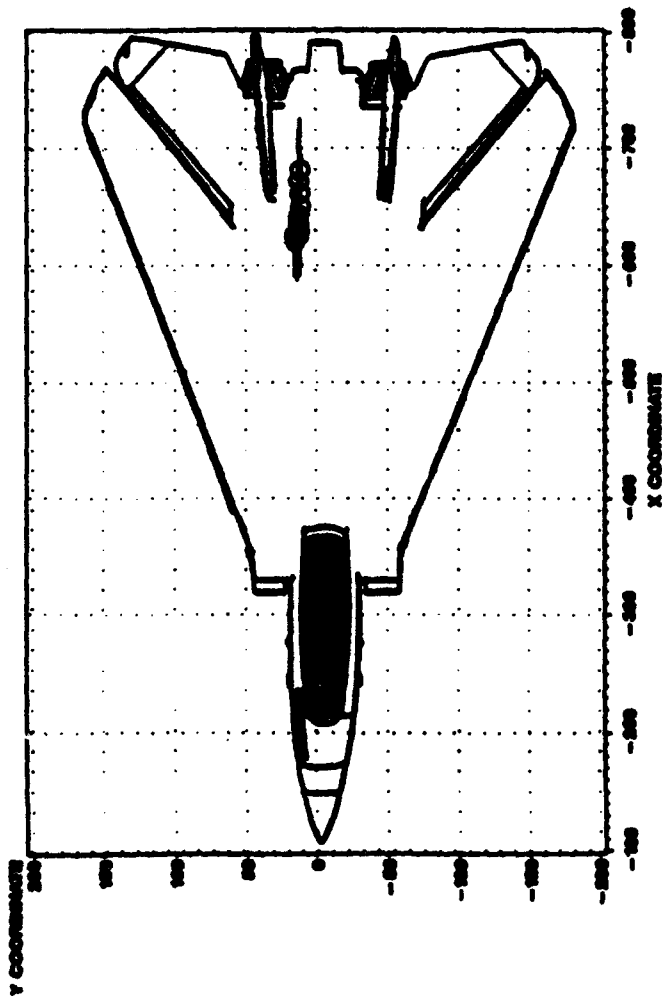
Peary did indeed reach the North Pole* ; a claim long since disputed by his critics. While this is quite an exotic application of the technology, the possibilities for additional aviation applications such as mishap reconstruction, carrier suitability, range tracking and overhead impact are just being realized. NAWC-AD continues to build upon its ability to rapidly configure for and provide quantitative photogrammetric data reduction and analysis. It can only be expected that the ease and accuracy of employing this technique will continue to advance.

* New Evidence Peary Reached The Pole; National Geographic; January, 1990; p44.

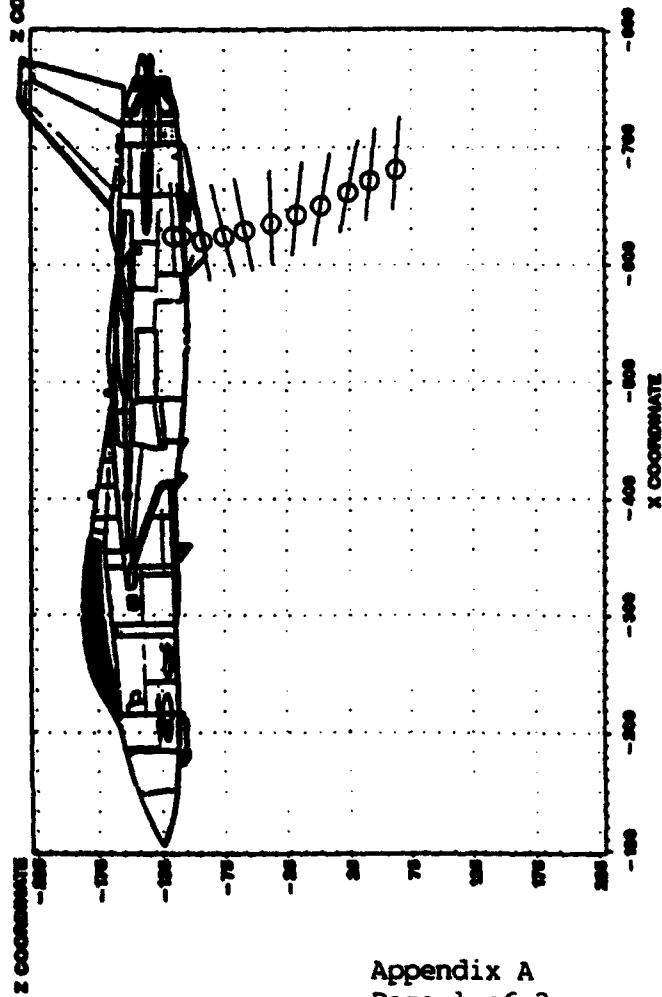
References

- A. Navy Technical Evaluation of the F-14A Air-to-Ground Weapons Compatibility; Naval Air Test Center report SY-189R-77; 7 FEB 78.
- B. AIM-9R/LAU-127 Evaluation on F/A-18 Aircraft; Naval Air Warfare Center report SA-30R-92; 6 MAY 92.
- C. Manual of Photogrammetry. Second Edition; American Society of Photogrammetry; George Banta; 1952.

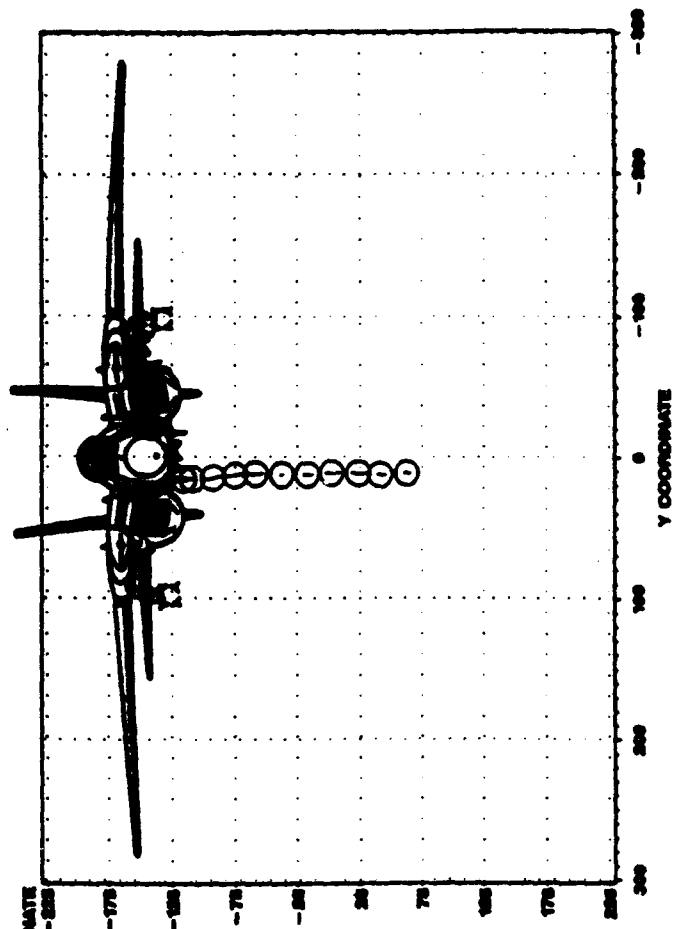
Y - X Position Of Bomb At Time T



Z - X Position



Z - Y Position



F-14D FLIGHT TEST PHOTOGRAMMETRICS DATA

DATE: SEPTEMBER 1, 1983

ID: EVENT 1

MACH	ALTITUDE	HZ	AOA	VELOCITY
SPEED	FT	POS	[°]	[KNOTS]
1.00	11200	0.50	-1.0	600

F-14D FLIGHT TEST PHOTOMETRICS DATA

DATE: SEPTEMBER 1, 1988

ID: EVENT 3

MACH

ALTITUDE

Nz

AOA

VELOCITY

SPEED

[ft]

[G]

[°]

[KIAS]

1.08

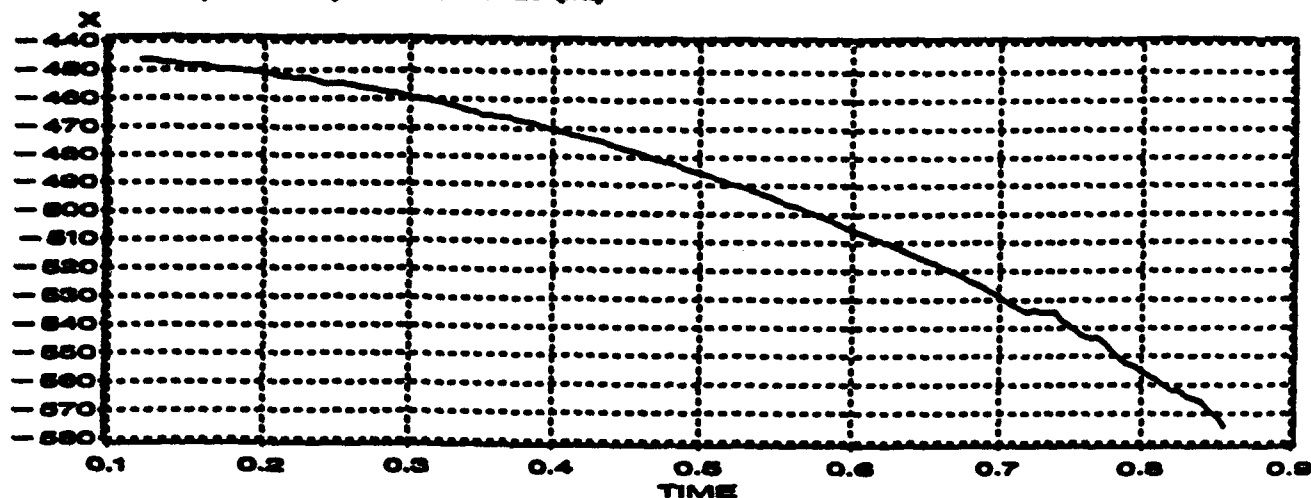
11800

0.4

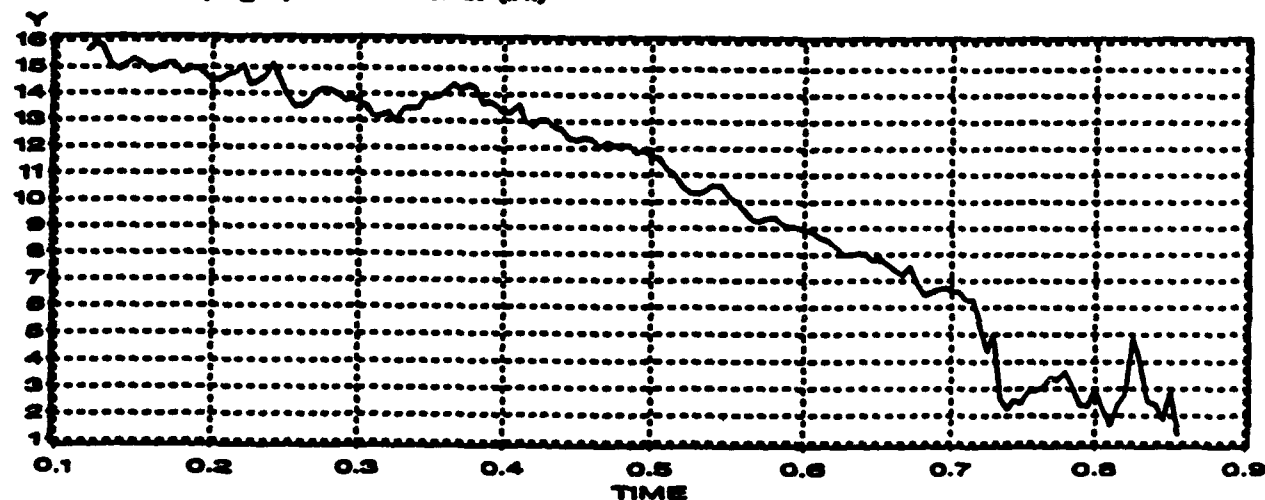
-2.5

600

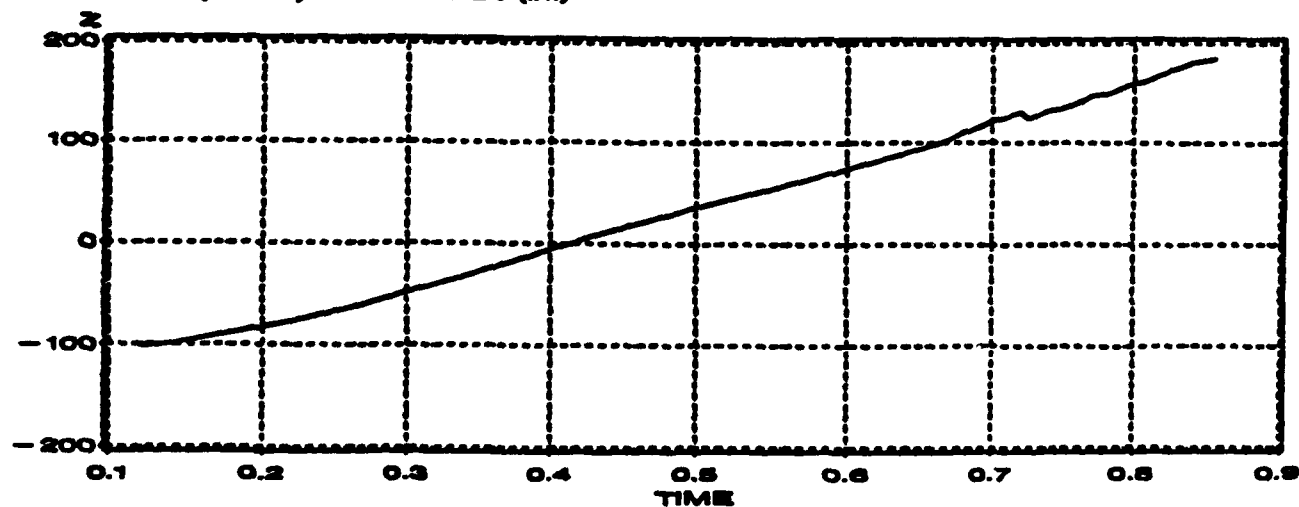
X-Position (Forward) WRT Aircraft (in.)



Y-Position (Right) WRT Aircraft (in.)



Z-Position (Down) WRT Aircraft (in.)

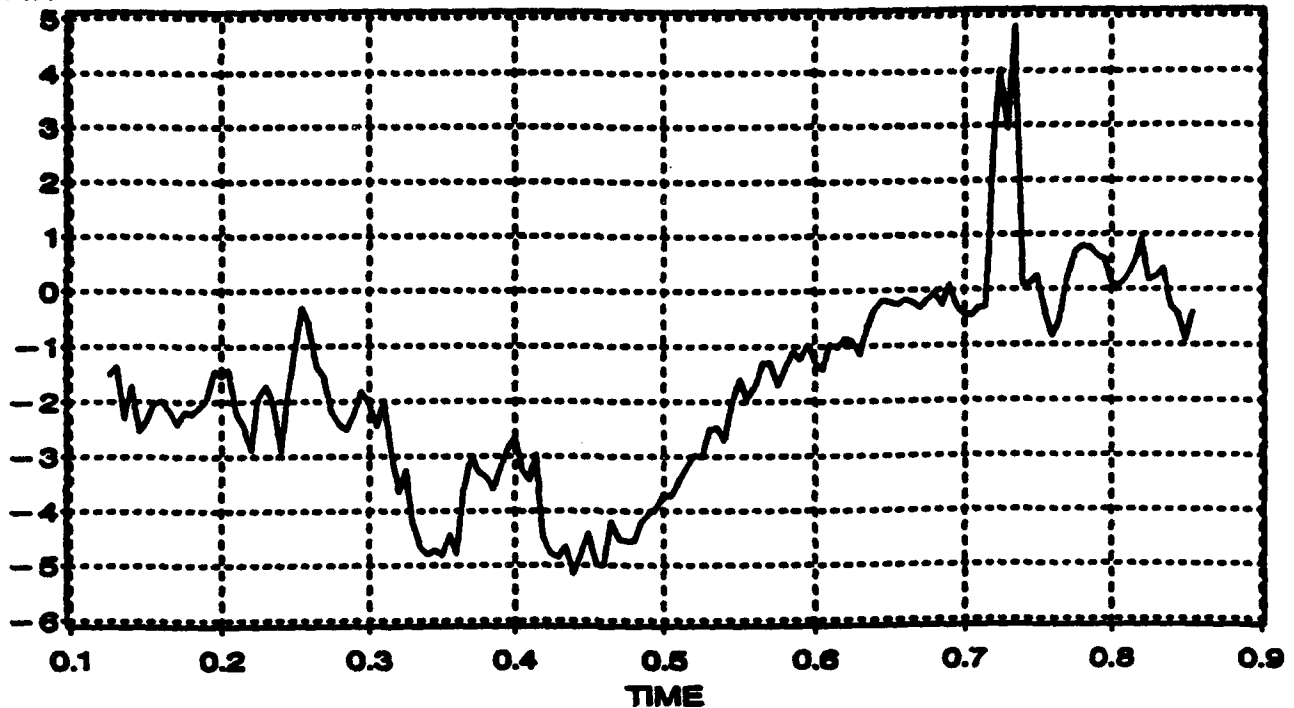


F-14D FLIGHT TEST PHOTOMETRICS DATA

DATE: SEPTEMBER 1, 1993		ID: EVENT 3		
MACH	ALTITUDE	Nz	AOA	VELOCITY
SPEED	[ft]	[G]	[°]	[KIAS]
1.09	11800	0.4	-2.5	800

Yaw Angle (Clockwise) WRT Aircraft (degrees)

YAW



Pitch Angle (Up) WRT Aircraft (degrees)

PITCH

